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Thermal tuning of MEMS buckled membrane actuator stiffness

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Abstract

The thermal tuning characteristics of a microelectromechanical systems (MEMS) buckled membrane exhibiting regions of both positive and negative stiffness is examined and analyzed using finite element method (FEM) simulation and through experimentation. The membranes are fabricated by releasing a silicon/silicon dioxide (Si/SiO_2) laminated membrane from a silicon on insulator (SOI) wafer. The difference in thermal expansion coefficients between Si and SiO_2 induces a compressive stress in the SiO_2 layer causing out-of-plane buckling of the membrane. This structure is found to have positive and negative stiffness regions when actuated with a transverse force. It is demonstrated that the stiffness of the membrane can be tuned by introducing a thermal stress to the membrane. Comparisons between localized heating of the membrane and even heating of the entire substrate are shown to affect the direction of the membrane deflection and tuning characteristics.

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Keywords: MEMS, thermal tuning, buckled membranes, tunable stiffness

1. Introduction

Buckling is a mechanical failure mechanism which instead of tearing or crushing causes a slender structural member to bow. With additional force the device will collapse. A membrane under uniform compression (Fig. 1)

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with a compressive stress greater than a critical stress, as determined by the dimensions and properties of the membrane, will buckle out-of-plane without any additional load. Buckling of these types of membranes has been thoroughly investigated and is well understood [1-4]. These buckled membranes have been shown to behave as springs with regions of positive and negative stiffness [5, 6] which may be tuned with the introduction of additional stress through localized heating of the membrane using resistive heating elements.

2. Membrane Analysis

Analysis of the total internal strain energy of a buckled membrane (Fig. 1(a)) shows that the membrane will exhibit three distinct regimes of stiffness (positive, neutral and negative) as it is deflected inward further (Fig. 1(b)). The total internal strain energy is given as,

$$U = 33\frac{Dh^2}{a^2}\left(\frac{\delta}{h}\right)^4 + 100\frac{Dh^2}{a^2}\left(\frac{\delta}{h}\right)^2\left(1-\frac{\sigma}{\sigma_{cr}}\right), \tag{1}$$

where U is the total internal strain energy, D is flexural rigidity of the plate given by Equation 2, h is the thickness of the membrane, a is the length of the membrane, δ, given by Equation 3, is the initial deflection of the membrane under a uniform compressive stress σ, and σ_{cr} is the critical stress of the membrane given by Equation 4 [7].

The flexural rigidity of the membrane, D, is given as,

$$D = \frac{Eh^3}{12(1-\nu^2)}, \tag{2}$$

where E is the Young's modulus, and ν is the Poison's ratio of the membrane [4]. The initial deflection of a membrane under uniform compressive stress, δ and the critical stress of the membrane, σ_{cr}, are given as Equations 3 and 4, respectively [4, 5]. If the total applied stress is below this critical stress, the membrane will not buckle.

$$\delta = \pm 2.298h\sqrt{\frac{\sigma}{\sigma_{cr}}-1} \tag{3}$$

$$\sigma_{cr} = 5.33\frac{D\pi^2}{ha^2} \tag{4}$$

The stiffness of the membrane, k, given by Equation 5, is the change in the restoring force of the membrane as it is deflected farther in a transverse direction. This can be represented as the second derivative of the total internal strain energy of the membrane given by Equation 1:

$$k = -\frac{\partial^2 U(x)}{\partial x^2} \tag{5}$$

The preceding equations predict that a membrane consisting of a 5 μm thick Si layer on top of a 2 μm thick SiO_2 layer will initially buckle 18 μm out-of-plane at room temperature and that with a 1000K increase in temperature,

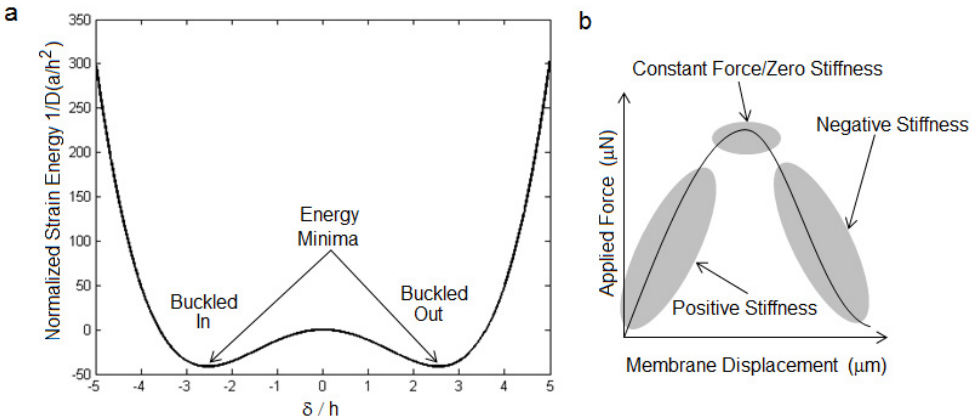

Fig. 1. (a) Internal strain energy of a buckled membrane vs. the displacement of the membrane. The two energy minima represent stability points; (b) applied force vs. displacement of a buckled membrane exhibiting three distinct regions of stiffness.

introduced by localized heating from a resistive heating element, the membrane deflection increases to 30 μm out-of-plane. This change in deflection directly correlates to a change in stiffness of the membrane as predicted by the internal energy vs. deflection curve as shown in Figure 2(a).

3. Results and Comparison of Previous Studies

FEM analysis of localized heating of the membrane confirms the predictions of the analytic model. As a result of an applied potential to generate the necessary localized joule heating of the membrane, the membrane deflection increases from 12 μm to 31.6 μm out-of-plane (Fig. 2(b)). Results from an earlier research [8] effort in which MEMS structures were used to measure thin film stress demonstrate that when the *entire substrate* is heated from room temperature to 110°C (Fig. 3(a)), the deflection of similar buckled membranes decreases from approximately 6.4 μm down to 6.2 μm.

The localized heating of the membrane induces a greater compressive stress in the membrane, leading to an increase in out-of-plane buckling whereas heating the entire substrate results in a tensile stress in the membrane which counteracts the compressive stress contributing to the initial buckling. Experimental results of a buckled membrane fabricated with a resistive heating element centered on the membrane confirm that localized heating of the membrane results in an increase of out-of-plane deflection (Fig. 3(b)).

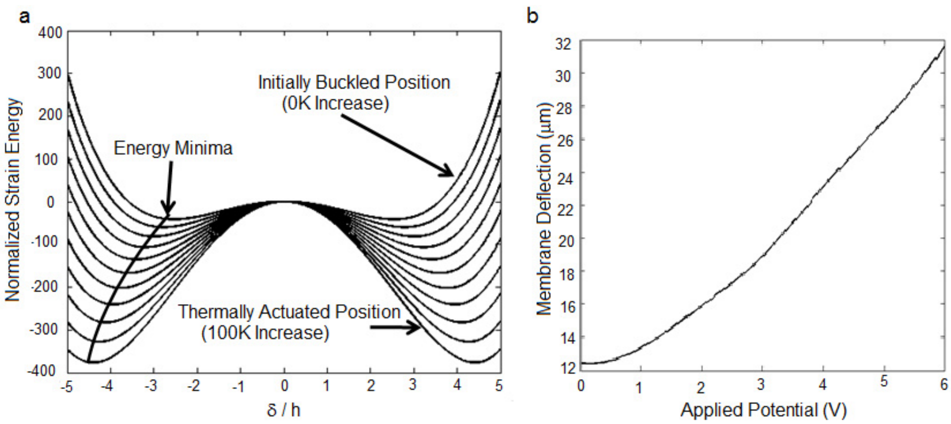

Fig. 2. (a) Plot of internal strain energy for different applied temperatures to the buckled membrane; (b) Membrane deflection distance increasing as applied potential to the localized heating element is increased.

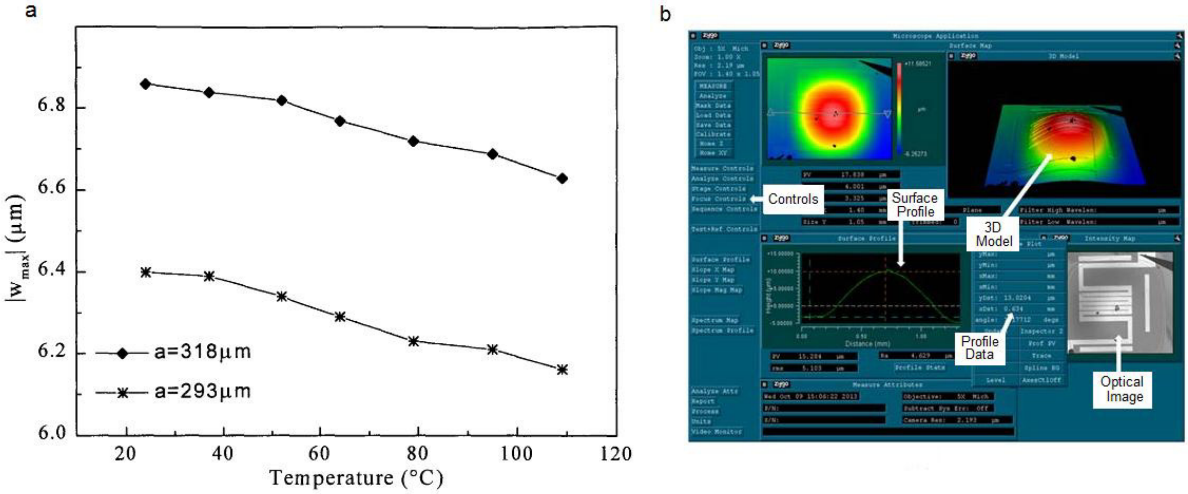

Fig. 3. (a) Plot of the deflection data for two different membranes as a function of temperature [9]. Note that as the temperature of the entire substrate is increased, the deflection of the membrane decreases counter to the behavior predicted and observed for localized heating; (b) Experimental data collection with a Zygo white light interferometer which verifies the model and FEM prediction that the membrane deflection increases out-of-plane when introduced to a localized heating source.

4. Conclusions

A model was developed to predict the deflection of a Si/SiO_2 buckled square membrane caused by thermal stress beyond its critical stress point. It was demonstrated that localized joule heating provides the ability to tune the stiffness characteristics of this membrane. Finally, it was shown that the deflection of the membrane can be increased or decreased depending on the heating method used.

Acknowledgements

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